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Office of Science

Department of Energy

Fundamentals of Geophysical Imaging

February 18 & 19, 2000

Gaithersburg, MD

FOREWORD

The Geosciences Research Program Symposium on "Fundamentals of Geophysical Imaging" is the seventh in a series of topically focused meetings for principal investigators in the program. Its objective is to provide an opportunity for investigators to give presentations and to engage in discussions of their Office of Basic Energy Sciences' supported research. Dr. Rick Ryerson of the Lawrence Livermore National Laboratory has kindly agreed to serve as host of the meeting, although we have come together in Gaithersburg, rather than Livermore CA. This meeting also serves to present the accomplishments of the program to our colleagues in other DOE offices and other Federal agencies in the Washington area. In addition to the recognition the symposium gives to all of the investigators, we traditionally also recognize one outstanding contribution from a DOE Laboratory Project and one from a University Project. These outstanding contributions are selected by our session chairpersons. We are fortunate to have as guest session co-chairs Professor David Kohlstedt from the University of Minnesota, Dr. Alan Jones from the Geological Survey of Canada, Professor Don Steeples from the University of Kansas and Mr. Dave Thomas from BP/Amoco. They join our Principal Investigator co-chairs Dr. James Berryman of Lawrence Livermore National Laboratory, Dr. Gregory Newman of Sandia National Laboratory, Dr. Michael Fehler Los Alamos National Laboratory, and Prof. Amos Nur, Stanford University. For their efforts on behalf of the investigators I thank them all. We are looking forward to an outstanding series of presentations.

Nicholas B. Woodward, Manager
Geosciences Research Program
Office of Basic Energy Sciences
U.S. Department of Energy

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Finite Difference Seismic Wave Propagation Modeling for 3D Isotropic Elastic Media

David F. Aldridge and **Neill P. Symons,** Geophysical Technology Department, Sandia National Laboratories, Albuquerque, New Mexico, USA, 87185-0750

The Geophysical Technology Department at Sandia National Laboratories has developed a seismic wave propagation algorithm appropriate for three-dimensional (3D) isotropic elastic media. The algorithm is based on the velocity-stress equations of linear elastodynamics, a set of nine, coupled, first-order partial differential equations. Solution yields the three components of the particle velocity vector $v_i(\mathbf{x},t)$ (i=1,2,3) and the six independent components of the stress tensor $\sigma_{ij}(\mathbf{x},t)$ (i,j=1,2,3 with $\sigma_{ij} = \sigma_{ji}$). An explicit, time-domain, finite-difference (FD) numerical scheme is used to solve these equations. Centered spatial and temporal FD operators possess 4th-order and 2nd-order accuracy in the discretization intervals, respectively. The nine dependent variables are stored on uniform, but staggered, spatial and temporal grids.

The computational algorithm is a direct numerical implementation of the governing partial differential equations of linear isotropic elasticity. No theoretical approximations, such as far-field distances, high frequencies, weak scattering, or one-way wave propagation, are adopted. Hence, the algorithm generates all seismic arrival types (P-waves, S-waves, reflections, refractions, multiples, mode-conversions, diffractions, head waves, surface waves, etc.) with fidelity, provided the spatial and temporal gridding intervals are chosen appropriately.

Special attention is devoted to representing the large variety of energy sources and receivers common in the seismic exploration arena. Most such sources may be idealized as one or more stationary point forces, dipoles, couples, torques, explosions/implosions, surface tractions, etc. Moving sources will be incorporated into the algorithm in the future. Multiple point sources may be activated simultaneously, with independently specified orientations, magnitudes, and waveforms. Hence, spatially extended source arrays may be simulated. Seismic energy receivers are considered to be particle velocity transducers (geophones) or acoustic pressure sensors (hydrophones). [Acoustic pressure is readily obtained by the algorithm via $p = (-1/3)\sigma_{kk}$, where σ_{kk} is the trace of the stress tensor]. Geophones may be oriented in any direction. Hence, multicomponent recording is easily simulated. Finally, general (i.e., fully 3D) recording geometries are permitted; sources and receivers may be distributed at arbitrary locations on and/or within the 3D earth model.

In order to simulate seismic conditions at the earth's surface, an explicit representation of a plane vanishing-stress boundary is included in the algorithm. Point traction sources, with arbitrary orientations, may be imposed on this surface. Nonplane surface topography will be incorporated into the algorithm in the future. However, preliminary testing indicates that a nonplane stress-free surface can be mimicked by assigning the material properties of air to grid nodes above the surface. Algorithm stability is maintained by making the earth/air interface gradational.

Significant computational resources are required to execute this 3D elastic wave propagation algorithm. In order to treat realistic-sized earth models (e.g., tens of millions of spatial gridpoints) and trace durations (e.g., thousands of timesteps) within reasonable execution times, parallel versions of the algorithm have been developed and sited on appropriate computational platforms. Parallel codes utilize Message Passing Interface (MPI) or Parallel Virtual Machine (PVM) coding protocols to maintain algorithm portability.

Synthetic seismograms replicating borehole experiments conducted at Bayou Choctaw Salt Dome in Louisiana have been computed, and are a reasonable match to the field recorded data, although with reduced spectral bandwidth. A primary goal of these field experiments is to record reflected energy from the nearby, nearly vertical, salt dome flank. Computational simulations of these data are currently being conducted in order to understand the various geological and geophysical factors that influence the strength, character, and even existence, of salt flank reflections.

Parameter Covariance Estimation for 2D and 3D Electromagnetic Inversion

David L. Alumbaugh, University of Wisconsin-Madison, Wisconsin
Gregory A. Newman, Sandia National Laboratories, Albuquerque, NM

Linear and non-linear methods have been implemented for appraising parameter accuracy in images generated with two- and three-dimensional (2D and 3D) non-linear electromagnetic inversion schemes that employ smoothness constraints on the model. When direct matrix inversion is employed, the aposterior model covariance matrix can readily be calculated. Plotting the diagonal of the linearized operator provides an estimate of how errors in the inversion process such as data noise and incorrect apriori assumptions map into parameter error, and thus provides valuable information about the uniqueness of the resulting image. Methods are also derived for image appraisal when the iterative conjugate gradient technique is applied to solve the inverse. An iterative statistical method is demonstrated to yield accurate estimates of the model covariance matrix as long as enough iterations are employed. This same technique can be applied to estimate the full non-linear covariance matrix. Examples and comparisons of the linear and non-linear image analysis techniques are provided on 2D and 3D synthetic cross well EM data sets, as well as a field data set collected at the Lost Hills Oil Field in Central California.

Characterization of Fluids and Fractures in Anisotropic Formations

Patricia A. Berge and **James G. Berryman**, Lawrence Livermore National Laboratory, Livermore, CA 94550

This project is part of a collaboration between LLNL, Stanford University, and Colorado School of Mines researchers, to develop seismic velocity analysis and seismic parameter estimation techniques for anisotropic rocks (CSM), and to carry out related laboratory (Stanford) and theoretical (LLNL) rock physics investigations to relate the seismic parameters to fracture and fluid distribution in the rocks, for application to fractured reservoirs. At LLNL, we are developing methods for using rock physics theories to relate seismic parameters in anisotropic rocks to fracture and fluid distribution.

Mixture theories for rocks can be applied to seismic velocity data to estimate parameters such as (1) porosity in sedimentary rocks, (2) amount of strength weakening materials (e.g., clay, fluid, high-temperature material including melt) present, and (3) the crack or fracture concentrations in regions where velocities are lowered by such weak zones. Mixture theories relate properties of solid and fluid constituents to overall properties of heterogeneous rock. Such methods developed in geophysics mainly by the petroleum industry and have been applied most commonly to isotropic, elastic systems for a wide variety of problems at various scales, including crustal and mantle structural studies, characterizing geothermal and petroleum reservoirs, and estimating subsurface properties at environmental cleanup sites. With the advancement of field techniques at various scales, it is now routine for high-resolution, 3D or 4D seismic data to be collected for many of these applications. Such high quality data warrant interpretation that includes the possibility of anisotropic and/or poroelastic systems.

Two very important results commonly used in rock analysis are due to Eshelby (1957) and Gassmann (1951). Eshelby showed that the strain inside an ellipsoidal elastic inclusion embedded in an otherwise homogeneous elastic medium is uniform if a uniform external strain is applied to the host medium. Eshelby shows further how to compute this uniform inclusion strain based on knowledge of properties of the host and inclusion. This result is very powerful, since it permits us to construct simple algebraic expressions that capture most of the behavior of constituents in composite elastic media. On the other hand, Gassmann's relation is often used to relate velocities in dry poroelastic rock to saturated rock velocities.

We investigate methods for combining Eshelby's results with Gassmann's results in order to model earth materials that are both anisotropic and poroelastic, particularly for rocks containing fluid-filled fractures.

Poroelasticity of Rocks

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The general thrust of the project has included the following four specific areas of research: (1) Extensions of previously developed rigorous bounds on the elastic constants of viscoelastic composites [Milton and Berryman, 1997]. Applications of these bounding methods together with related effective medium estimates to analysis of rocks are currently under study with the goal of updating the classic work of Budiansky and O'Connell by incorporating modern effective theories and bounds into the viscoelastic analysis. (2) Extending [Pride and Berryman, 1998] the volume averaging technique in order to clarify and extend the theory of poroelasticity to more complex media (two or more solid constitutents) and more complex physical contexts (allowing fractures as well as matrix porosity) than has been the case in the past. (3) Extending previous work on double-porosity/dual-permeability analysis for fractured rocks to quantities that can be easily measured in laboratory and field tests. Recent progress has been made on wave propagation at finite frequencies [Berryman and Wang, 2000] and for situations where the data available are those concerning the constituent materials, so that a microscopic model of the dependence of double porosity parameters on constituent properties can be developed. (4) Generalization of Eshelby's formulas for a single ellipsoidal elastic inclusion to poroelasticity and thermoelasticity [Berryman, 1997] and using these to produce new quasistatic and scattering equations in rock physics analysis and thereby allowing us to develop a new and much more powerful formulation of effective medium theory which will in turn generalize earlier effective medium work of the PI and his collaborators.

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Using GPR to Image 3D Facies Heterogeneity in Outcrop: Implications for Reservoir Modeling

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Outcrop analogs are commonly used to determine the spatial arrangement of different rock types that represent "flow-units", "flow-barriers and flow baffles" in subsurface reservoirs. 3D reconstructions of reservoir architecture using outcrop analogs are hampered by the availability of only 1-D or 2-D outcrop cross sections. GPR provides data about reservoir properties and facies geometry from within the 3-D volume. This fundamentally enables us to produce 3-dimensional quantification of facies heterogeneity. GPR data is also highly analogous to 3-D seismic data in the way it is processed and interpreted.

In this study, we integrate outcrop photomosaics, measured sections, permeability measurements and 100MHz 2D and 3-D Ground Penetrating Radar grids, tied to borehole data. This allows us to fully document the 3-D facies architecture of stacked river channel deposits formed in a large ancient delta deposit of the Cretaceous-age Ferron Sandstone in Utah.

On photomosaics, four erosively-based channel elements were mapped. The lowermost channel overlies coal-bearing, delta-plain mudstones formed in a brackish swamp. The next overlying channel 2 consists of meter-thick, sandstone beds floored by mudstone intraclast conglomerate. The sandstone beds are draped with thin mudstones that show rare burrows, indicating periodic marine incursion within a laterally accreting point bar. Channel 3 locally erodes into both channels 1 and 2 and consists of thick sandstone with thick mudstone intraclast conglomerates. Channel 4 lies at the top of the outcrop and contains medium-grained cross-bedded to convolute stratified sandstone. Specific radar facies and permeability structures characterize each channel element.

The most important potential flow barriers in the system are interpreted to be the mudstone intraclast conglomerate along basal scours and the mudstone drapes at the top of laterally-accreting inclined beds within the channel 2. The spatial continuity and variation of these flow barriers may be determined by modeling 3-D experimental variograms of the GPR amplitudes in each radar facies as well as by direct mapping of thicker layers.

GPR allows us to "see" into the outcrop and develop truly 3D images of the facies architecture as well as the all important flow barriers and baffles. The geological variability, including effective reservoir properties, can be calibrated to GPR attributes. This potentially allows porosity and permeability to be mapped directly using the 3-D GPR data. GPR also provides a link to using 3D seismic and to development of reservoir geophysics technology.

Conceptual information from 3-D images can drive subsurface interpretation. 3-D data also gives us information about the shape of things, versus just apparent length or width in 2-D cross sections. Statistical information about architectural elements can be used in object-model-based flow models such as modeling stochastic shales. These fine-scaled 3-D models can be in turn be used to test and develop more sophisticated, or more efficient reservoir and aquifer modeling tools, by developing new upscaling techniques and pseudofunctions.

Magnetotelluric Imaging with Minimal Computer Resources

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Modern advances in computation machinery have vastly improved our ability to extract subsurface electric conductivity structure from surface magnetotelluric (MT) data using either natural or controlled sources. However, in both industrial and research applications it is often desirable to invert large multi-dimensional data sets in the field in order to guide data collection. This puts a premium on algorithms that are efficient enough to be used on laptop computers. Two classes of algorithms have proven suitable: the rapid-relaxation inverse (RRI) and conjugate gradient (CG) techniques. Both involve computing approximate model updates. Practical RRI algorithms remain faster than CG and are now available for both natural and controlled sources and for land and seafloor use. However, RRI has difficulty inverting important aspects of the data, such as the vertical to horizontal magnetic field transfer function and also does not fully implement desirable forms of the model structure penalty. Furthermore, neither algorithm explicitly computes the Frechet derivatives of the data with respect to the model parameterization, and thus do not allow application of common resolution analysis techniques. Progress is being made on getting around the limitations of RRI and we are currently working on an improved 3-D version.

are also making progress in speeding the CG algorithm. Finally, we have developed techniques for pre-inversion data winnowing and repair that can guarantee that the data being input to the inversion algorithm are physically plausible and thus are guaranteed to have an inverse. Their application greatly improves the convergence of all algorithms.

Seismic Modeling and Imaging Using Recursive One-way Wave Propagation

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Seismic migration imaging is one of the most important processing steps used by the petroleum industry to process exploration seismic data. The basic concept of seismic migration is to back project a seismic wavefield recorded on the Earth's surface to obtain an image of the reflectivity of the Earth's subsurface. There are various approaches for doing this. All are limited by the extremely large computational requirements or by the reliability with which they back project the recorded wavefield. Practical seismic migration techniques are based on assumptions that allow this processing step to be accomplished relatively rapidly; however for large datasets it still requires significant resources to migrate a large 3D dataset using state-of-the-art parallel computers. The backprojection is accomplished using a modeling operator acting on surface seismic data with time reversed. Thus, to improve image quality while reducing its computational cost, we seek methods for seismic modeling that are both fast and reliable.

In collaboration with the Modeling and Imaging Laboratory of the University of California at Santa Cruz and several US Oil companies, we have been developing and testing a suite of new methods for obtaining improved seismic images of the Earth's subsurface in regions of geological complexity. The methods are based on one-way wave propagation. We have investigated methods using the Born approximation, the Rytov approximation, and an extension of the Born approximation that we call the quasi-Born approximation. All of our methods have a greater range of applicability than the conventional approach used to model one way wave propagation, called the Split-Step Fourier method, which is based on a narrow-angle Rytov approximation. Our approaches are slightly more expensive computationally than the Split-Step Fourier method but they are more reliable when medium heterogeneity is strong and our methods handle larger propagation angles from the main propagation direction.

We have investigated the capability of our methods for doing both modeling and imaging. We have found that they are extremely reliable for modeling wave propagation in cases where forward scattering dominates. For such modeling, the methods are 20 to 500 times faster than finite difference solutions of the full acoustic wave equation. For imaging, we find that our methods give images that are superior to those obtained using either the conventional Kirchhoff migration approach with single-valued traveltime tables or the Split-Step Fourier method. Tests using numerical data show that significant reflectors in images obtained are more clearly delineated than in images obtained using conventional migration approaches. In addition, Kirchhoff and Split-Step Fourier images often have incorrect reflector locations whereas our images have reflectors in the correct locations. On field data, we have clearly delineated reflectors located beneath overhanging salt that have not been delineated using Kirchhoff migration. Thus, our methods provide valuable information for targeting petroleum drilling that is not available from other methods.

Space Plasma and Space Weather

S. Peter Gary, Los Alamos National Laboratory, Los Alamos, NM 87545

Space weather refers to conditions on the sun and in the solar wind, magnetosphere, ionosphere, and thermosphere that can influence the performance and reliability of space-borne and ground-based technological systems. Geomagnetic storms and substorms are two examples of space weather phenomena which can have terrestrial impact, particularly with respect to the induction of geomagnetic fluctuations. This talk summarizes space plasma research at Los Alamos National Laboratory which is supported by the DOE Geosciences Program and which addresses space weather issues in general and geomagnetic variations in particular.

Numerical Modeling of Time-Lapse Seismic Data

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Reservoir monitoring using time-lapse seismic data offers considerable potential for improving reservoir management by providing direct feedback on the movements of fluids within the relevant formations. However, there are also many potential sources of error or uncertainty in such data analysis, such as changes in acquisition parameters or poor calibrations of rock properties like porosity with seismic velocities. Acquisition related problems might be minimized by permanent receiver installations or by taking other steps to ensure compatibility, but relating seismic observations to rock properties will remain a challenging problem since there are no simple, error-free relationships between these quantities. In our work, we examine the impact of such uncertainties using a rapid and efficient modeling scheme that allows us to quickly consider multiple scenarios.

The numerical modeling incorporates two approximate, rapid methods for simulating both the movements of pore fluids in the reservoir and the seismic wavefields that would be reflected by the reservoir. Fluid flow simulations are accomplished with a streamline simulator. This approach begins by computing streamlines from a velocity field that has been generated using finite difference or finite element methods, and the primary advantages are that the streamlines do not have to be updated often and the transport equations are decoupled form the underlying grid. Seismic reflection experiments over the reservoir are simulated using a ray-Born method, which uses ray tracing to account for wave propagation in an overburden that is assumed to be unchanged during production of the reservoir. The Born approximation accounts for wavefields scattered from localized perturbations to the background model, a natural application of this approximation since the changes in reservoir properties in time and space are restricted to the reservoir volume.

The key link between the two modeling schemes is the model of rock physics that predicts seismic properties based on pore fluid properties and reservoir properties such as porosity and permeability. We apply the Gassmann equation, combined with some empirical results for the dependence of elastic moduli on effective pressure (REF), for this purpose. As an example, we consider a reservoir structure with stochastic models of porosity and permeability, where the elastic moduli are related to the porosity using cloud transforms to reproduce the nonuniqueness that is generally observed in laboratory measurements. We demonstrate the predicted sensitivity of seismic data to such quantities as variations in the drained bulk modulus of the reservoir formation, which is easy and relatively quick to calculate using the streamline and ray-Born modeling methods.

Future work will extend these methods to consider the monitoring of CO_2 sequestration efforts using seismic methods. The model will be extended to include geochemical reactions to provide a more realistic simulation of the effects that will be important for long term sequestration.

A Nonlinear Mesoscopic Elastic Class of Materials

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It is becoming clear that the elastic properties of rock are shared by numerous other materials (sand, soil, some ceramics, concrete, etc.). These materials have one or more of the following properties in common: strong nonlinearity, hysteresis in stress-strain relation, and discrete memory. Primarily, it is the material's compliance, the mesoscopic linkages between the rigid components, that give these materials their unusual elastic properties. It can be said that these materials have *nonlinear mesoscopic elasticity* and encompass a broad class of materials. Materials with nonlinear mesoscopic elasticity stand in contrast to liquids and crystalline solids whose elasticity is due to contributions of atomic level forces, i.e. materials with *atomic elasticity*. Atomic elastic materials are well described by the traditional (Landau) theory of elasticity; however mesoscopic elastic materials are not. Mesoscopic materials are well described by the P-M (Preisach-Mayergoyz) model of nonlinear elasticity developed by Guyer and McCall. A sequence of experiments on numerous materials illustrate the evidence of nonlinear mesoscopic elastic behavior. In experimental analysis a surprising discovery was made*: damaged atomic elastic materials behave as mesoscopic elastic materials*. It is significant that the nonlinear mechanism(s) in mesoscopic elastic materials remains a mystery.

Characterization and Variability in Earthquake Patterns

William Klein, Boston University, Boston, MA

To understand the stability of earthquake faults we need to understand the physical mechanism behind earthquakes. We have studied a cellular automaton version of a slider block model of an earthquake fault. Assuming a long range stress transfer we were able to identify at least four different types of earthquakes with different physical mechanisms. Three of these different types comprise the Gutenburg-Richter scaling region. The fourth type, which is the largest, consists of ``breakout events" that occur due to instabilities in the stress field. I will discuss the theoretical and numerical investigations that have led to these conclusions.

Subcritical Creep Compaction of Quartz Aggregates under Dry and Fluid-Saturated Conditions

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The compaction and diagenesis of sandstones that form reservoirs to hydrocarbons depend on mechanical compaction processes, fluid flow at local and regional scales, and chemical processes of dissolution, precipitation and diffusional solution transport. This research addresses the volumetric creep and deformation of quartz aggregates, the transition from isochemical brittle deformation to fluid-assisted solution-transfer creep, identification of mechanisms of solution transfer creep, and evaluation of mechanical and chemical rate laws for clastic reservoir lithologies.

Volumetric creep rates have been measured for quartz aggregates made up of St Peter sand and disaggregated Arkansas novaculite (d = 300 to 35 _m) subjected to T = 150 ^{o}C and an effective pressure $P_e = (P_c - P_p)$= 34.5 MPa (well below critical values of P* for cataclastic flow) while 1) vented to the atmosphere, 2) exposed to water vapor (P_{H2O} = 0.21 MPa), 3) saturated with a static fluid at pore pressures of 1.4 to 12.8 MPa, and 4) saturated with percolating fluid at a flow rate (0.12 ml/hr) sufficiently low for steady-state dissolution and transport of silica. Quartz aggregates vented to atmosphere exhibit small strain rates that follow a logarithmic creep relation at rates down to ~3 x 10^{-10} s^{-1} and show little grain size sensitivity. Quartz aggregates loaded sequentially while vented, exposed to H_2O vapor, and saturated by fluid exhibit systematic increases in creep rate (from ~3 x 10^{-10} s^{-1} to ~4 x 10^{-9} s^{-1} and ~6 x 10^{-9} s^{-1}, respectively). Strain rates under wet conditions follow logarithmic creep relations of similar form but quantitatively distinct from the relation exhibited under dry conditions. Creep rates of samples with percolating fluid are yet another order of magnitude greater than those measured with static fluids saturating pores.

During closed system, wet experiments, static pore fluids initially consist of distilled water while fluids withdrawn from pores of samples following loading are highly supersaturated (195 ppm) with respect to _-quartz at T and P_p. During open system, slow-flow experiments, distilled water entered one end of each sample, while fluids measured at the opposite end were saturated (160 ppm) at P_e = 0 and supersaturated (~170 ppm) at P_e = 34.5 MPa. Under both open and closed wet conditions, strain rates b depend on grain size d as $\beta \;\alpha\; d^{-1}$.

The mechanisms of time-dependent creep under dry, vented conditions are unknown, but trace atmospheric H_2O may have assisted subcritical crack growth and grain rearrangement. These and other mechanisms that do not require silica transport are expected to contribute to the strain of wet quartz aggregates under closed system conditions. Strain rates of St Peter sand aggregates under open system conditions can be accounted for almost entirely by SiO_2 loss rates and grain convergence, assuming that dissolution occurs only at grain contacts and that internal precipitation is negligible. However, strain rates of fine novaculite samples are large by comparison with SiO_2 loss rates, implying that dissolution is not the sole or governing time-dependent mechanism of compaction.

Joint Inversion for Subsurface Imaging

K.H. Lee, H.F. Morrison, **M. Hoversten**, **D. Vasco**,Lawrence Berkeley Laboratory, Berkeley, CA

Objectives: To develop a joint inversion methodology using geophysical data, specifically the data from in-hole, surface-to-borehole and borehole-to-borehole electromagnetic and seismic surveys, and the in-hole gravity survey, to extrapolate borehole log or core data to the interwell volume. The underlying concept of using the geophysical data to predict the hydrologic properties is borrowed directly from the well-established field of well logging. Here borehole geophysical measurements of sonic velocity, electrical resistivity and density are used jointly to estimate porosity and saturation (usually oil/water saturation). Cross-plots of different physical properties are often reliable site-specific indicators of lithology and, in conjunction with pumping tests, site-specific correlations can be established between the physical properties and permeability. It is the objective of this proposal to extend these concepts to the mapping of hydrological properties in the interwell volume using both in-hole and large-scale cross-hole and hole-to-surface geophysics.

Project description: Accurate mapping of geophysical and hydrological parameters are increasingly more important in the broader study of groundwater supply, development of long-term injection strategy for CO_2 sequestration, characterization and monitoring of petroleum reservoirs and environmental remediation processes, and in almost all aspects of subsurface engineering in general. These parameters are presently estimated either by interpolating between values obtained from core samples or well logs in an array of wells, or by inversion of well test, and interference test, data directly to hydrologic conductivity. The former provides a richer distribution of properties but requires holes spaced proportionally to the scale of the subsurface heterogeneity. The latter is a notoriously ill-posed inverse problem and moreover is inapplicable in the unsaturated zone. Either of these methods is significantly improved if additional information related to the desired properties is included. Geophysical methods are available which can map the distribution of seismic velocity and electrical conductivity beneath the surface and between holes. These physical properties are dependent on density, porosity, fluid saturation, clay content, and in some circumstances, permeability. While general quantitative relationships are elusive, on a site-specific basis, this geophysical data can provide spatial information that is ideal for the interpolation of well log data and for constraining or conditioning the inversion of data from pumping tests. Indeed the relationship between seismic properties, conductivity, and the hydrologic parameters are now so well known that we propose to develop a means to invert the geophysical and well data to a distribution of properties that jointly satisfies all the field data. This task integrates geophysical and hydrological inversions subject to site specific empirical relationships and borehole information as constraints. With the success of the proposed joint inversion we can achieve optimum subsurface geophysical and hydrological parameters that simultaneously satisfy geophysical and hydrological measurements.

Seismic Signatures of Fluids in Anisotropic Rocks

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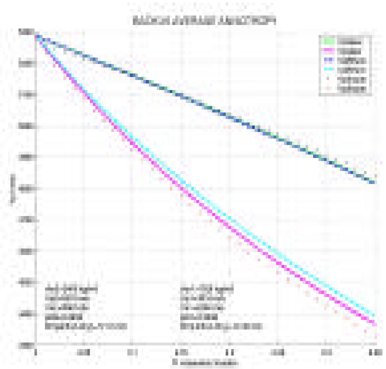
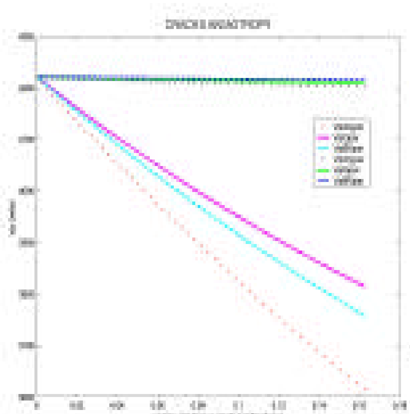
The subsurface is often anisotropic due to aligned thin layers or aligned cracks and fractures. For various reasons such as incomplete data, or modeling complexity and cost, the anisotropy may not be properly taken in to account. This is often the case when doing a fluid substitution calculation in porous rocks. The summary describes briefly two results related to seismic signatures of anisotropic rocks: a) a reformulation of the Backus theory from depth to time, making it more directly relatable to seismic processing, and b) an estimate of the uncertainty introduced by ignoring anisotropy when computing fluid effects on seismic velocities in anisotropic porous media. The essence of Backus theory is that it allows a heterogeneous stack of thin layers to be replaced, in the long wavelength limit, by a single, homogeneous equivalent layer, with anisotropic elastic properties. Layers with thicknesses Z_j, elastic compliance S_j, and density R_j, are replaced by the equivalent medium with properties: $Z_{eq} = \sum Z_j$, $S_{eq} = \sum (S_j Z_j) / \sum Z_j$, $R_{eq} = \sum (R_j Z_j) / \sum Z_j$. However, instead of describing the individual layers in terms of elastic compliance and density, they can also be parameterized by their seismic impedance I_j and one-way traveltime, T_j. Reformulating the Backus equations, the equivalent media properties are given by: $I_{eq} = [\sum(T_j I_j)/\sum(T_j/I_j)]^{1/2}$, $T_{eq} = [\sum(T_j I_j) \sum(T_j/I_j)]^{1/2}$. These equations exactly translate Backus theory from depth and elastic properties to time and impedance, transplanting Backus' relations from the physical world to the data processing world of traveltime and reflectivity. Often rocks may be anisotropic, but we may not have the full anisotropic elastic stiffness tensor. We may have measurements of only velocities along the principal direction. How much of an error is introduced if we take the velocity along one direction only, and do fluid substitution assuming isotropy? We apply two different techniques in the fluid substitution problem; one is Gassmann's fluid substitution, implying that we assume our samples to be isotropic. The other approach is Brown and Korringa fluid substitution, using the complete elastic compliance tensor. By comparing both results we evaluate the effect of assumption of isotropy in fluid substitution. The figures compare the computed fluid effects on seismic velocities in anisotropic rocks for thin layers (top) and aligned cracks (bottom). Hudson's model was used for the aligned cracks. In both cases, ignoring anisotropy does not lead to any significant error for the fluid effects on velocities parallel to the aligned features (i.e. perpendicular to the symmetry axis). However, a significant error is introduced in the velocities perpendicular to the layers and cracks. Assuming isotropy may lead to underestimating fluid effects in thin layered media, while they may be overestimated in cracked media.





3D Magnetotelluric Modeling and Inversion

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We have formulated three-dimensional (3D) forward and inverse solutions for magnetotelluric (MT) applications. Finite difference methods are used to efficiently compute predicted data and cost functional gradients. A fast preconditioner has also been developed at low induction numbers to reduce the time required to solve the forward problem. We demonstrate a reduction of up to two orders of magnitude in the number of Krylov subspace iterations and an order of magnitude speed up in time needed to solve a series of test problems. For the inverse problem, we employ a nonlinear conjugate gradient solution and show that only six forward modeling applications per frequency are typically required to produce the model update at each iteration of the scheme. This efficiency is achieved by incorporating a simple line search procedure that calls for a sufficient reduction in the cost functional, instead of an exact determination of its minimum along a given descent direction. Additional efficiencies in the scheme are sought by incorporating preconditioning to select optimal search directions, which accelerates solution convergence. Even with these efficiencies, the solution's realism and complexity are still limited by the flop rate and memory of serial processors. To overcome this barrier, the scheme has been implemented on a parallel computing platform where tens to thousands of processors operate on the problem simultaneously.

Acoustic Signatures of Fractured Rock: Implications for Fracture Imaging

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Present methodologies for modeling and extracting fracture properties from seismic data utilize approximations in which fracture systems are represented by their zero-frequency, equivalent anisotropic elastic moduli. These equivalent moduli have been used to predict AVO (amplitude versus offset) and shear wave splitting produced by multiple, aligned fractures that are many wavelengths in planar extent, and closely-spaced relative to the seismic wavelength. However, because the equivalent medium approach is based on a static approximation, it does not predict changes in amplitudes resulting from reflections off fractures, nor potentially diagnostic wave phenomena such as diffractions off fracture tips, and the generation of fracture-supported waves, such as interface, head, and channel waves. Our research has utilized numerical simulations and laboratory modeling to investigate the partitioning of incident body waves into these various fracture-supported waves, and the subsequent radiation of these waves back into body waves for single and multiple fracture systems. Factors which control the generation efficiencies of the fracture-supported waves and subsequent radiation of these waves into body waves, such as wave frequency, and the presence of fracture tips and spatially varying fracture stiffnesses will be presented. The implications of these results to fracture imaging using seismic waves will also be discussed.

Rock Physics for Seismic and SAR Characterization and Monitoring of Reservoir Fluids and their Recovery

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The future of geophysics includes the potential to track reservoir fluid distribution during the life of a field through the use of periodic geophysical snapshots or time lapse geophysical monitoring. To this end our research focuses on the advanced use of rock physics for interpreting remote measurements for accurate detection and monitoring of subsurface fluids using 2 methods: (a) seismic, both surface and borehole; and (b) differential interferometric synthetic aperture satellite radar (DInSAR) measurements.

a).Seismic. The speed of elastic waves in rocks is generally sensitive to pore fluid properties and pore pressure, and their temporal variations during recovery. This sensitivity provides a physical basis for the direct seismic interrogation of large volumes of the subsurface with variable degree of resolution. The method of seismic monitoring is applicable to onshore fields but is especially promising for offshore reservoirs because of the contemporary hardware and software that allow one to easily generate and detect waves in water.

b.)Synthetic Aperture Radar (SAR). Because of the compressibility of porous rocks the withdrawal and injection of fluids into the subsurface causes subtle deformation of the earth's surface. Interferometric differentiation of pairs of SAR images acquired over time by satellites can map the surface deformation field associated with fluid injection and/or withdrawal. Long-term (up to two years) interferograms allow one to record land subsidence due to changes in the subsurface pore pressure and pore volume in producing subsurface reservoirs. SAR can be used only on land. Because of the ease of acquiring and processing SAR data, we consider necessary to explore its applicability to monitoring onshore oil and gas recovery.

Applicability of Remote Measurement Techniques

	Characterization		Monitoring	
	Onshore	Offshore	Onshore	Offshore
Seismic	Yes	Yes	Yes	Yes
SAR	No	No	Yes	No

The following is a scheme of our workflow:

SEISMIC	**SAR**
Site Selection and Data Organizing	Site Selection
Core Measurements Well Log Data Analysis	SAR Data Processing for Surface Elevation Changes
Site-Specific Rock Physics Transformation	Input to Poroelastic Theory from Core Measurements and Well Log Data Analysis
Applying Rock Physics Transformations to Seismic Volumes of Velocity and Impedance AVO analysis	Poroelastic Modeling and Interpretation of Surface Level Changes for Pore Pressure and Fluid Volume Changes
Characterizing Reservoir and Fluids Monitoring Feasibility Study	Inferring Fluid Flow Direction
Verifying Results (Production Data)	Verifying Results (Production and Flow Simulation Data

Porous Rocks with Fluids: Seismic and Transport Properties

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I. PERMEABILITY ESTIMATION FROM ROCK IMAGES
We introduce a new procedure for prediction of permeability from rock thin sections, using direct 3-D flow simulation by Lattice-Boltzmann method. From a rock image, we determine the porosity and the auto correlation function by image processing. We then generate a 3-D porous rock model using geostatistics and using numerical methods simulate fluid, electrical flow through these realizations as well as the elastic response. The results show much better agreement with laboratory measurements than standard empirical relation

II. METHANE HYDRATE:
1. WAVE SPEED MEASUREMENTS. We have developed a novel method for simultaneously measuring compressional and shear wave speeds through pure, dense, polycrystalline methane hydrate. Samples are grown in a custom-built cylindrical pressure vessel by slowly heating granular water ice in a pressurized methane atmosphere while shear and/or compressional wave speed measurements are taken. We measured a compressional wave speed of 3360 ± 50 m/s and a shear wave speed of 1800 ± 50 m/s.

2. ELASTIC MODELS SEDIMENTS OF CONTAINING GAS HYDRATE. We developed effective medium models for the elastic properties of hydrate-sediment systems. We apply this model to sonic and VSP data from ODP Hole 995 and obtain hydrate concentration estimates consistent with hydrate estimates obtained from resistively, chlorinity, and evolved gas data. Also, calculated velocities closely match velocities observed in well logs from Northwest Eileen State Well No. 2 onshore Alaska.

III. DYNAMIC POROELASTICITY AND LIQUEFACTION IN SOFT SEDIMENTS
The causes for repeated liquefaction of soils and sands due to earthquakes remain an outstanding scientific puzzle. We discovered using dynamic poroelasticity that when an poroelastic layer is subjected to a cyclic stress pore pressure can build up significantly due to a resonant mode of Biot’s type II wave. In soft sediments (e.g. sand), where the shear modulus is less than 0.3Gpa, this pore pressure can exceed the total overburden pressure and cause liquefaction.

Imaging Heterogeneity in Fractured Media

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A strategy for reducing carbon dioxide (CO_2) emissions into the atmosphere from power plants burning fossil fuel is to capture CO_2 and sequester the CO_2 in subsurface reservoirs. Candidates for geological sequestration include depleted oil and gas reservoirs, deep saline aquifers, and underground coal beds. Though these subsurface reservoirs often differ in lithology and structure, fractures are common to all. Seismic methods have the potential to be a quantitative diagnostic tool for monitoring CO_2 sequestration in reservoirs, but progress is hindered by incomplete understanding of the effect of multi-scale heterogeneity (which scatter different wavelengths differently) within fractured rock on seismic wave propagation and is hindered by incomplete understanding of relationship between the seismic response and the hydraulic properties of the fractured rock mass.

An important issue that affects CO_2 sequestration in subsurface reservoirs is whether seismic techniques can identify rapid flow paths (fractures) that could compromise the hydraulic integrity of the reservoir. We have a begun a numerical investigation on the interrelationships among the hydraulic, mechanical, and seismic properties of a fracture. Preliminary results indicate that (a) fractures that are very compliant support more fluid flow than stiffer fractures, and (b) the relationship between fluid flow through a fracture and fracture specific stiffness hinges on the spatial correlation of the aperture distribution. Seismic wave attenuation and velocity can be used, remotely, to determine fracture specific stiffness. Thus, this suggests that seismic data can be used to determine fluid flow through fractures if we can accurately map the stiffness of fractures.

Our ability to determine fracture specific stiffness using seismic methods hinges on our ability (1) to differentiate the individual stiffness of each fracture in a fracture network or fracture set, (2) to understand the effect of fluid saturation/ chemical alteration on fracture specific stiffness, and (3) to understand the spatial variation of fracture specific stiffness within a single fracture. We have begun measurement of seismic wave propagation (1) through dry and saturated multiple parallel synthetic fractures subjected to a range of stresses; (2) through induced saturated fractures in limestone subjected to chemical alteration; and (3) through a synthetic fracture subjected to non-uniform stress conditions.

The Electrical Properties of Rocks During Boiling

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The electrical properties of fluid saturated rocks are sensitive to many factors including porosity and microstructural properties, the nature and amount of pore saturant, temperature, and pressure. The composition and phase of the pore saturant (i.e., liquid versus steam or gas, water versus other liquids) are very important factors that can dominate electrical properties because most rocks are excellent insulators *in vacuo*, but saturation with insulating liquid (or steam) decreases their resistivity by eight orders of magnitude or more. An objective of this work is to understand the relationships among electrical resistivity, microstructure, and boiling in the rock. As water in pores flashes to more resistive steam, electrical pathways are cut-off and the resistivity of the sample increases. Conceptually, if boiling-induced changes are sufficiently large, such regions could be sensed remotely using surface- and borehole-based electrical surveys. Employing such techniques could provide the means to evaluate changing geothermal reservoirs, tracking steam fronts during enhanced oil recovery or environmental remediation. Tracking of insulating injectate has direct application to monitoring the geological sequestration of carbon dioxide.

Laboratory measurements were performed on hydrothermal breccia, metashale, welded tuff, sandstones, and fused glass bead samples from 23 to 250°C and pressure between 100 kPa and 10 MPa. Pore and confining pressures were measured and controlled separately. A dilute NaCl solution (~0.01 m) with conductivity (σ) = 1.5 mS/m) was used as the saturating fluid. Impedance magnitude and phase were measured between 100 Hz and 1 MHz utilizing platinum electrodes and a four-electrode two-terminal pair technique. A typical experimental and measurement sequence consisted of saturating the sample, jacketing, installation, bleeding the system of air, pressurization (confining followed by pore at a 2:1 ratio), and heating. Pore pressure was lowered stepwise as the boiling field was entered.

Tracking the resistivity of the rocks as boiling conditions were achieved revealed a number of interesting phenomena. First, boiling occurs gradually rather than all at once and is controlled by the pore size distribution in a process we refer to as heterogeneous boiling. A model is being constructed that takes into account the capillarity of the small pores (submicron diameter). Individual pores do not boil until the capillary pressure (or suction) is offset by a corresponding lowering of the overall pore pressure. Each pore that boils effectively cuts off a conductive pathway with the result that as pressure is continually lowered a higher percentage of the pores are boiling. The electrical signature of this transition was most pronounced for the tightest rocks (tuffs and metashales) with fine pores and less in the higher porosity rocks (sandstones) with large pores and a narrow pore size distribution. The fused glass bead samples studied are similar to well-sorted sandstones with the absence of water-clay interactions. Preliminary results on these samples show results similar to those of sandstones with the majority of the sample boiling at pressures slightly below that predicted by the P-T diagram of water. These samples also demonstrated porosity enhancement and permeability modification caused by salt deposition and crystal shattering during the boiling process.

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract Number W-7405-ENG-48 and supported specifically by the Geoscience Research Program of the DOE Office of Science within the Office of Basic Energy Sciences, Division of Engineering and Geosciences.

Images of Space-Time Patterns in Complex Earth Systems

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Energy-related facilities such as nuclear reactors, government research laboratories and commercial establishments are often at serious risk in areas of tectonic instability, such as for example the west coast of the United States, as well as in other countries. Damage in such events can far exceed the estimated $200 billion in losses from the Kobe, Japan earthquake of 1995, or the $30 billion in losses from the 1995 Northridge, California Earthquake, or the $10 billion in losses from the 1989 Loma Prieta, California, earthquake. Estimates by the insurance industry groups put potential economic losses from repeats of the 1857 Fort Tejon and 1906 San Francisco earthquakes, both in California, in excess of $1 trillion. With several nuclear reactors in California, as well as the Lawrence Livermore, Lawrence Berkeley, and Sandia National Laboratories and many other facilities at risk, the US Department of Energy has been motivated to assess the magnitude of potential disasters that may occur.

Our previous work has been focussed on the development of numerical simulations of the dynamical processes associated with earthquake occurrence so that analytical and predictive ideas could be systematically developed and tested, with a view towards developing techniques to eventually forecast these large destructive events. Since it is clearly not possible to conduct "laboratory experiments" on real faults, it is therefore intuitively obvious that the only alternative is the development of numerical simulations that capture aspects of the real, non-linear physics. One of the crucial early results (1995) of this program of simulations has been that in the mean field conditions expected to hold for real earthquake fault systems, the system of simulated earthquake faults demonstrates ergodicity and thus possesses properties of equilibrium systems. The mean field regime is attained when the range of interactions, or coupling strength between elements of the system, becomes large. This is an enormously useful result since there exists a vast literature on the analysis of equilibrium systems. Moreover, it is clear that since much of the dynamics of equilibrium systems can be predicted, we can expect that many of the dynamical properties of earthquake fault systems should be predictable as well.

Building upon these ideas, we have recently developed a means of describing the time development of patterns in seismic activity in simulations, then applied the methods to real earthquake faults in southern California and elsewhere. We find that it is possible to define a "pattern dynamics" that can be used to forecast the future evolution of seismic activity in the system. In this talk, I will describe these techniques and show how images of future hazard probability can be constructed. Statistical likelihood ratio tests indicate that our images have considerable predictive capability. It seems likely that this method can be developed into a practical means of earthquake forecasting in the near future.

Constraints on geothermal and magmatic processes from GPS, gravity, and seismic data

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The mechanical coupling of fluid flow and rock deformation has important implications for energy production as well as for a wide range of geologic processes. Fluid/rock interactions are important in hydraulic fracturing, steam injection and water flooding in oil reservoirs, production induced ground deformation, earthquake generation, liquid injection in geothermal reservoirs, and in coupled magmatic groundwater processes. We developed simple analytical approximations for induced stress changes within reservoirs due to changes in pore-pressure and temperature and demonstrated that these approximations are consistent with in situ changes in least horizontal compressive stress caused by production. Production induced stressing can act to favor normal faulting within, and particularly at the margins of, producing reservoirs. This can enhance fracture permeability and prolong production.

We also developed analytical methods for computing temperature, fluid pressure, and stress perturbations induced by injection of cold fluids in geothermal reservoirs. The principal result of this work has been to show that in the near field of an injector, thermal stresses can exceed pore-pressure changes for realistic injection scenarios. Thermal stresses thus play an important role not only in triggering seismicity but in changing fracture aperture and altering hydraulic conductivity.

Some geothermal fields in volcanic calderas, like Long Valley, and are subject to rapid deformation and seismicity. It has been suggested that uplift and earthquake activity in some caldera systems is driven by flow of hydrothermal fluids rather than by magmatic intrusion. It is obviously crucial, from both resource and hazards perspectives, to differentiate between these processes. To this end we repeated precise gravity measurements in Long Valley caldera first surveyed by the USGS in the early 1980s. These measurements reveal a decrease in gravity of as much as -107±6 µGal (1 µGal = 10^{-8} m/s^2) centered on the uplifting resurgent dome. A positive residual gravity change of up to 64±15 µGal was found after correcting for the effects of uplift and water table fluctuations. Assuming a point source of intrusion, the density of the intruding material is 2.7 x 10^3 to 4.1x10^3 kg/m^3 at 95% confidence. The gravity results require intrusion of silicate magma, and exclude in situ thermal expansion or pressurization of the hydrothermal system as the cause of uplift and seismicity.

Earth's Electrical Conductivity as Viewed from the Laboratory

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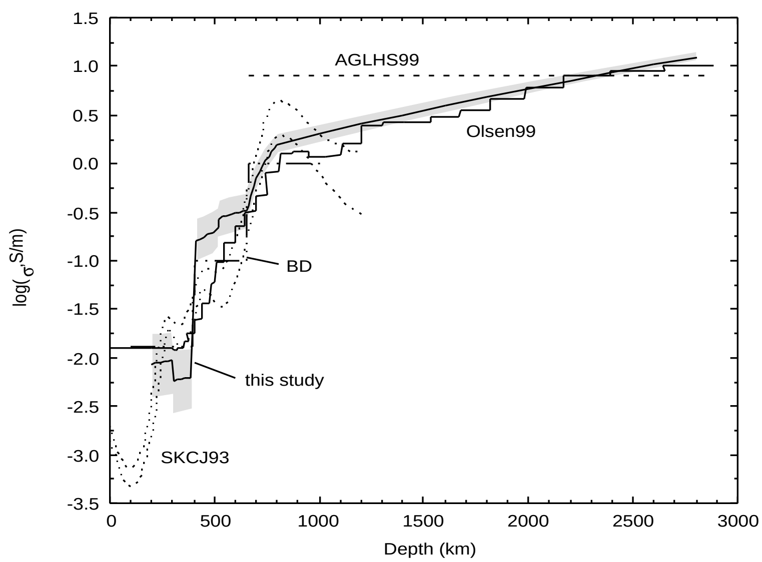
Electrical conductivity of the deep Earth has been a topic of study since Lahiri & Price's initial study of 1939 which started with applying geomagnetic variations to look down into the mantle. Such geophysical pictures provide information that is needed for understanding the boundary conditions affecting the geodynamo, magnetic propagation outward from the core, core-mantle coupling, and changes in the length of day.

Recent laboratory measurements of electrical conductivity of mantle minerals are used in forward calculations for mantle conditions of temperature and pressure. The electrical conductivity of the Earth's mantle is influenced by many factors, which include temperature, pressure, the coexistence of multiple mineral phases, and oxygen fugacity. In order to treat these factors and to estimate the resulting uncertainties, we have used several spatial averaging schemes for mixtures of the mantle minerals and have incorporated effects of oxygen fugacity. The effective medium theory averages lie between the Hashin-Shtrikman bounds in the whole mantle. A laboratory-based conductivity-depth profile was constructed using the effective medium theory average. Comparison of apparent resistivities calculated from the laboratory-based conductivity profile



with those from field geophysical models shows that the two approaches agree well.

Fig. 1 – Laboratrory-based conductivity model for Earth’s mantle in comparison with several recent geophysical models.

The Role of Surface Contamination on Seismic Attenuation in the Vadose Zone

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Our long-term objective is the remote detection of contaminants in the vadose zone. To complement other methods, such as electrical or magnetic, we have chosen to look at the effect of certain contaminants on the attenuation of seismic waves.

Early laboratory experiments in Lyon's Sandstone showed a very large attenuation when a surfactant was added to the water in the pores. The attenuation changed its frequency dependence for at least 530 hours, at which time the measurements were abandoned. The observed behavior could not be explained with any of the attenuation models available. Rather than starting to model this obviously complicated system, we decided to learn about individual mechanisms we could think of that might cause this behavior.

We employed some very simple and also some sophisticated experimental arrangements to study in some detail of flow over surfaces. In the process we confirmed some of the existing models, but also found that changes in surface energies can have a large effect on the flow of two phases of liquid (air and water in our case) in narrow spaces. Furthermore we found that the kinetics of wetting and un-wetting of a surface cause time dependent and thus frequency dependent resistance to flow; i.e. frequency dependent attenuation. From a battery of experiments we have been able to measure the appropriate time dependent changes and construct a model that satisfies the attenuation and stiffness data measured on single dime shaped cracks.
We have started preliminary experiments involving bacteria as contaminants and detect significant changes as the bacteria grow and subsequently die.

We are in the design stage of a large-scale laboratory experiment and are seeking collaboration for the planned first phase of a field experiment.

Finite Difference Modeling and AVO, AVA Analysis of Fractured Reservoirs

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Amplitudes of seismic waves as a function of offset and azimuth reflected from fractured reservoirs depend on the degree of fracturing, saturation, and orientation of the fractures. We studied the sensitivity of amplitudes, and their dependence on distance and azimuth, on formation properties. These numerical results show that fracture orientations can be resolved with greatest certainty. Fracture density and saturation are best resolved at large offsets with incidence angles of 30° or greater.

Analysis of 3-D seismic reflection data from a fractured carbonate reservoir showed that amplitudes for lines perpendicular to fractures and parallel to fractures were distinctly different. There were other attributes in the data, in addition to anisotropy, that indicated other properties of the fractured reservoir were also affecting seismic reflection amplitudes.

Characterization of Naturally Fractured Reservoirs using Azimuthally Dependent Seismic Signatures

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The results described here were obtained by the Center for Wave Phenomena (CWP) within the framework of the project ``Three-dimensional analysis of seismic signatures and characterization of fluids and fractures in anisotropic formations'' (other participants include LLNL and Stanford University). Our research is aimed at developing efficient velocity analysis and parameter estimation methods based on 3-D (azimuthal) variation in basic seismic signatures, such as traveltimes and prestack amplitudes. The inversion can then be used to evaluate the physical properties of azimuthally anisotropic fractured formations and study the lithologic properties of source and reservoir rocks.

We showed that the azimuthally dependent normal-moveout (NMO) velocity of reflection events represents an ellipse in the horizontal plane, even if the medium is arbitrarily anisotropic and heterogeneous. NMO ellipses can be obtained from conventional-spread 3-D reflection data using a technique of azimuthal velocity analysis developed at CWP. Our processing methodology, which also includes a correction of moveout velocities for lateral heterogeneity and anisotropic layer-stripping, was applied to a 3-D data set acquired by ARCO in the Powder River Basin, Wyoming. P-wave NMO ellipses from several major reflectors allowed us to reconstruct the depth-varying fracture direction and estimate the magnitude of azimuthal anisotropy. The orientation of the interval NMO ellipses in all layers are in agreement with the known fracture trends in the area and the results of shear-wave splitting analysis.

Assuming that the azimuthal anisotropy is caused by a single set of vertical fractures makes it possible to obtain fracture parameters important for reservoir characterization. We developed several inversion algorithms to evaluate the crack density and infer the type of fracture infill from different combinations of seismic signatures (e.g., NMO velocities of P-and PS-waves, shear-wave splitting, AVO of P- and PS-reflections).

Imaging along Strike Variations in the Structure of the San Andreas Fault: A Comparions of the Cholame, Parkfield and Hollister Segments

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Since 1994, high-resolution magnetotelluric (MT) exploration has been used to image the shallow structure of the San Andreas Fault in Central California. In 1994 profiles were acquired on the locked segment at Carrizo Plain and at Parkfield where the fault undergoes periodic rupture with characteristic M=6 earthquakes (Unsworth *et al*.,1999). In 1997, the first year of this project, two additional profiles were collected at Parkfield to determine if the low electrical resistivity observed close to the 1966 hypocenter is typical of the entire Parkfield segment. A profile was also collected on the Cholame segment than represents a transition from the creeping to locked segments. During the second year of fieldwork (1999) two profiles were collected on the creeping segment near Hollister. This presentation will focus on (a) the detailed analysis of the 1994-7 data and (b) an initial analysis of the 1999 Hollister data.

(a) Parkfield and Cholame segments: The three MT profiles on Middle Mountain have been inverted with identical processing parameters to systematically examine if the structure of the fault is changing along the segment. A range of inversion algorithms has been applied to the data. The results indicate that the fault zone conductor initially described by Unsworth *et al.*, (1997) is present on each profile. Its depth extent is constrained to be between 1500 and 3000 m. There is a hint that the conductive zone deepens to the southeast and shows a correlation with the shallow seismicity (Unsworth *et al*., 2000). The Cholame Valley profile crossed the San Andreas Fault near the *en echelon* offset. The MT data imaged a shallow, conductive, basin that deepens to the west. No evidence of a vertical, fault zone conductor was found. Thus a significant change in the geoelectric structure of the fault occurs between Middle Mountain and the Cholame Valley. Additional MT exploration around the village of Parkfield could determine exactly where this change occurs.

(b) Central creeping segment near Hollister: In October and November 1999 magnetotelluric data were collected on two profiles that crossed the creeping segment of San Andreas Fault. On each profile continuous magnetotelluric data were collected close to the fault, while further from the fault measurements were made at single stations located a few kilometres apart. The southern profile was centred on Bear Valley. The northern profile crossed both the San Andreas and Calaveras Faults near Paicines. Owing to cultural noise from powerlines and pipelines, remote reference data from more than 100 km away is needed to obtain reliable estimates of apparent resistivity and phase. Initial resistivity models for both these profiles will be presented.

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Seismic modeling and imaging using screen propagator and wavelet transform

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Generalized screen method for modeling and imaging is based on the ONE RETURN APPROXIMATION, which is a multiple forward-scattering, single backscattering (MFSB) approximation. Since the work of elastic complex screen, many variants of the GSP (Generalized Screen Propagators) for modeling and imaging has been developed by our group (the Modeling and Imaging Laboratory, UCSC), in collaboration with Los Alamos National Laboratory. The GSP method filled the gap between the full-wave finite difference method and the ray method, and is several orders of magnitude faster than the full-wave methods. In the same time it keeps all the essential features of the full-wave methods and can deliver even better image quality than the full-wave methods. For modeling, the methods for calculating elastic wave reflection synthetic seismograms using elastic screen propagators, and half-screen propagators for Lg wave propagation in complex crustal waveguides have been developed and improved. These fast 3D elastic modeling methods can provide the seismic community and the industry with handy tools for modeling, inversion, and interpretation.

For imaging problem, only forward propagation is relevant and the phase accuracy of the wavefront is more important than the amplitude accuracy. Therefore a high-frequency asymptotic phase-matching has been applied to the screen propagators to correct the phase errors for large-angle waves introduced by the one-way approximation. Currently two of GSP are implemented and tested: the modified pseudo-screen propagator and the wide angle Pade-screen propagator. The method circumvented the difficulty of the perturbation approach and has excellent wide-angle performance for strong contrast media. Images of complicated subsalt structures and overthrust structures from synthetic and field data showed significant quality improvement over the convertional Kirchhoff depth migration methods. Since the screen propagator method is a wave equation based method, amplitude information is inherently better preserved than the Kirchhoff migration. The method has great potential for high-resolution, high-fidelity subsurface imaging for complicated structures where ray-theory based methods fail.

For the future development, we have done some work on the wave propagation in wavelet domain. The newly developed fast wavelet transform (WT) is considered to be a revolutionary breakthrough in signal analysis/processing. In the same time frame, there has been significant progress in one-way wave propagation theory and algorithms, including the fast acoustic and elastic generalized screen propagators developed by our group. The cross-breeding of these two new developments has the potential of revolutionizing modeling and imaging techniques for complex Earth media. We have shown that the one-way wave propagator in wavelet domain, which is called the beamlet propagator, is a highly sparse matrix and has both the space and wavenumber domain localizations. The beamlet migration can retain the wide aperture of a full-aperture operator and at the same time reduce substantially the computation time.

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